

# Polarimetric Diagnostics of Unresolved Chromospheric Magnetic Fields

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## ABSTRACT

For about a decade, spectro-polarimetry of He I  $\lambda 10830$  has been applied to the magnetic diagnostics of the solar chromosphere. This resonance line is very versatile, as it is visible both on disk and in off-limb structures, and it has a good sensitivity to both the weak-field Hanle effect and the strong-field Zeeman effect. Recent observations of an active-region filament showed that the linear polarization was dominated by the transverse Zeeman effect, with very little or no hint of scattering polarization. This is surprising, since the He I levels should be significantly polarized in a conventional scattering scenario. To explain the observed level of atomic depolarization by collisional or radiative processes, one must invoke plasma densities larger by several orders of magnitude than currently known values for prominences. We show that such depolarization can be explained quite naturally by the presence of an unresolved, highly entangled magnetic field, which averages to give the ordered field inferred from spectro-polarimetric data, over the typical temporal and spatial scales of the observations. We present a modeling of the polarized He I  $\lambda 10830$  in this scenario, and discuss its implications for the magnetic diagnostics of prominences and spicules, and for the general study of unresolved magnetic field distributions in the solar atmosphere.

*Subject headings:* Sun: chromosphere – Sun: prominences – Sun: magnetic fields – line: profiles – polarimetry

Magnetic diagnostics of the chromosphere, and in particular of prominences and spicules, is receiving increasing attention and motivation from the solar community. There is in fact a growing agreement that mapping the magnetic field in these critical regions of the solar atmosphere is fundamental for our understanding of processes like coronal heating, the acceleration of the solar wind, and the release of coronal mass ejections, that have a direct influence on the heliosphere and on the associated phenomena of space weather. Despite the strong demand for these critical observations, there have been relatively few attempts to measure magnetic fields in the chromosphere and corona. This is mainly due to the heavy science requirements imposed on spectro-polarimetric

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instrumentation by this type of observations, and to the intrinsic difficulty of the inversion and interpretation of scattering polarization data.

Spectral line polarization is produced when symmetry-breaking processes occur in the interaction of radiation with matter. These can be due to the presence of external magnetic or electric fields (Zeeman and Stark effects), or an anisotropy in the excitation of the atoms (by radiation or particles) leading to scattering polarization. We can expect both types of processes to be always present in the solar atmosphere. However, their corresponding polarization signals differ significantly. In particular, the presence of unresolved fields affects those signals in characteristic ways. For example, for a completely random distribution of magnetic fields within the resolution element of the observations, the polarization by the Zeeman effect must vanish in the mean, whereas the scattering polarization is only reduced in amplitude by a characteristic factor of 1/5 with respect to the zero-field case. When both processes occur, and the random magnetic field has a non-zero mean, the observed signal will be a complex mix of Zeeman effect and scattering polarization, with a significant depolarization contributed by the random part of the magnetic field.

Recent observations of the He I multiplet at 1083 nm in an active-region (AR) filament (Kuckein et al. 2009) have shown that the linear polarization was dominated by the transverse Zeeman effect, corresponding to magnetic fields in the 500 G–1000 G range. The modeling of the forward-scattered radiation of He I  $\lambda 10830$ , under the assumption that the filament plasma is illuminated by the underlying photosphere, indicates instead that the linear polarization should be significantly affected by the atomic alignment of the upper term  $2^3P$ , induced by radiation anisotropy, even in the presence of field strengths of the order of  $10^3$  G. A basic assumption of the Zeeman-effect model is that the atomic levels of He I are “naturally” populated, and therefore completely depolarized. In contrast, in the scattering-polarization model, which includes atomic polarization, we were forced to introduce an ad-hoc reduction factor for the radiation anisotropy (varying between 0 and 1) in order to reproduce the observed depolarization of the He I levels. Obviously both models lack a physical basis for such depolarization, which is the question taken up in this Letter.

The characteristic rate,  $\gamma$ , at which atomic polarization is generated in the levels of a spectral line by resonance scattering, is inversely proportional to the radiative lifetimes of the levels. In particular, for He I  $\lambda 10830$ ,  $\gamma_u \sim A_{ul} \approx 10^7 \text{ s}^{-1}$  and  $\gamma_l \sim B_{lu}J$ , where  $A_{ul}$  and  $B_{lu}$  are the Einstein coefficients, respectively for spontaneous emission and absorption, between the upper ( $u$ ) and lower ( $l$ ) levels, and  $J$  is the average intensity of the radiation field. If we assume  $J \approx (1/2)B_\nu(T=5800\text{ K})$ , then  $\gamma_l \approx (3/20)\gamma_u$ .

Once created, atomic polarization is not easily destroyed, unless competing processes (e.g., external fields, collisions, radiative ionization and recombination) modify the polarization of the atomic levels at a much higher rate than both  $\gamma_l$  and  $\gamma_u$ . A strong magnetic field (i.e., with Larmor frequency  $\nu_L \gg \gamma_{l,u}$ ) can depolarize atomic levels (through the Hanle effect) very efficiently, although the degree of residual polarization strongly depends on the geometry of the field. For example, scattering polarization is completely destroyed by a strong magnetic field with inclination

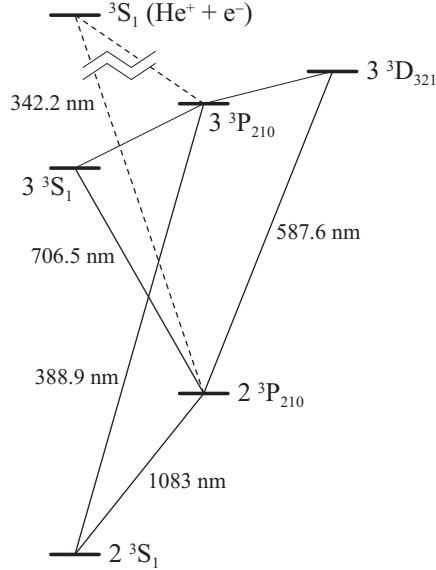


Fig. 1.— Model atom for the statistical equilibrium of the triplet species of He I. The lowest five terms constitute the system of bound-bound transitions. The model is extended to include photo-ionization and recombination involving the  ${}^3\text{P}$  states, by adding a fictitious bound state  ${}^3\text{S}_1$  corresponding to the ground state of He II.

$\vartheta_B = \arccos 1/\sqrt{3} \approx 54.7^\circ$  from the direction of illumination. This effect may be invoked to explain the AR filament observations described in Kuckein et al. (2009). However, those authors report profiles showing strong atomic depolarization even for nearly horizontal magnetic fields.

Atomic collisions with an isotropic distribution of perturbers (neutral or charged) are a possible mechanism of atomic depolarization. 1) Inelastic collisions with electrons are not significant for the statistical equilibrium of He I at the typical densities of prominences ( $N \sim 10^{10}\text{--}10^{11} \text{ cm}^{-3}$ ). The observation of scattering polarization at the limb in these structures also points to the fact that atomic excitation is dominated by resonance scattering rather than thermal processes. It is possible that AR filaments may be significantly denser than quiescent prominences, leading to a larger contribution of thermal processes. However, following van Regemorter (1962), collisional excitation of He I  $\lambda 10830$  by electrons would require  $n_e \approx 4 \times 10^{13} \text{ cm}^{-3}$ , in order to be comparable with radiative excitation. This would imply gas densities 3 to 4 orders of magnitude larger than currently known values in quiescent prominences (e.g., Tandberg-Hannsen 1995) for electron collisions to dominate the formation of He I. 2) We can estimate the rate of elastic collisions of He I atoms in the  ${}^3\text{P}$  state with neutral hydrogen, using  $\gamma_H \sim \langle \sigma v \rangle n_H \approx 8 \times 10^{-9} n_H \text{ cm}^3 \text{ s}^{-1}$  (Lamb & Ter Haar 1971). Hence, to efficiently depolarize the upper levels of He I  $\lambda 10830$  by collisions with neutral hydrogen it should be  $n_H \gg 10^{15} \text{ cm}^{-3}$ . 3) Elastic collisions with electrons have received little attention in the literature. Hirabayashi et al. (1988) report experimental cross-sections at  $T = 2000 \text{ K}$  for Ne I in the  $2p_2$  level. If we extend their results to the case of He I at plasma temperatures  $T \sim 10\,000 \text{ K}$ ,

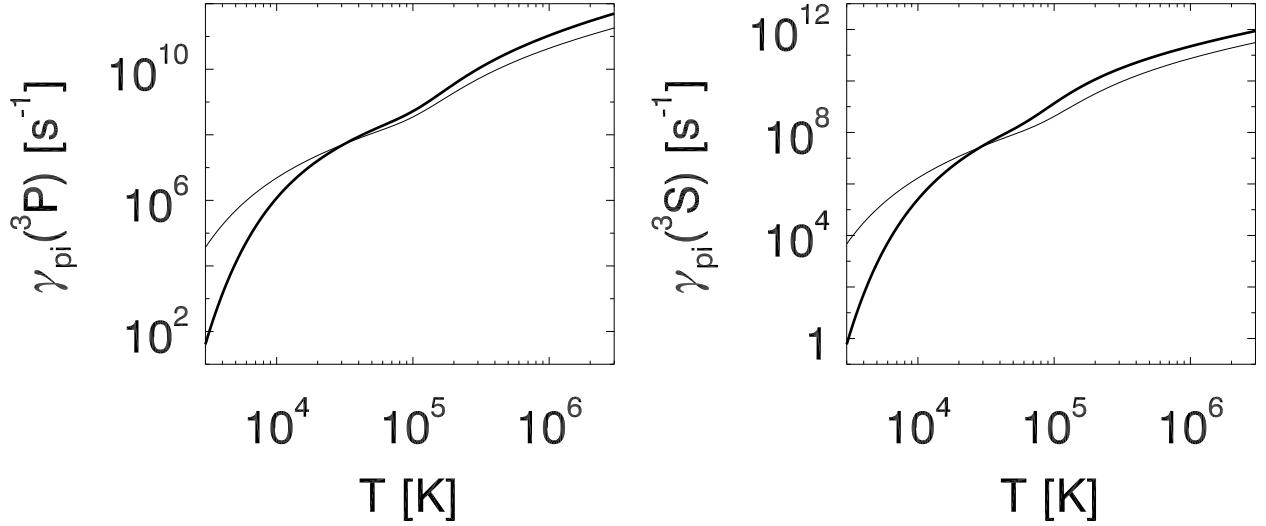


Fig. 2.— Photo-ionization rates for the lowest  ${}^3\text{P}$  terms (left) and  ${}^3\text{S}$  terms (right) of neutral helium, as a function of the temperature of a Planckian illumination. The thick lines correspond to the  $2^3\text{X}$  terms, and the thin lines to the  $3^3\text{X}$  terms.

we find  $\gamma_e^{\text{el.}} \sim 10^{-6} n_e \text{ cm}^3 \text{ s}^{-1}$ . Efficient depolarization of the upper state of He I  $\lambda 10830$  would then imply  $n_e \gg 10^{13} \text{ cm}^{-3}$ , at which line excitation by thermal electrons should dominate over radiative excitation (see above). In conclusion, collisional depolarization of the He I levels seems to consistently require plasma densities that are exceptionally large for a typical prominence. On the other hand, the densities of AR filaments are poorly known, and the possibility of such high plasma densities merits further investigation.

We consider next the role of radiative processes like photo-ionization and recombination for the depolarization of He I levels. Figure 1 illustrates the atomic model commonly employed for the study of resonance scattering polarization in He I lines (e.g., Landi Degl’Innocenti 1982; López Ariste & Casini 2002; Asensio Ramos, Trujillo Bueno, & Landi Degl’Innocenti 2008). This model has been successfully applied to interpret the Stokes profiles of the D<sub>3</sub> line at 587.6 nm in solar prominences (Bommier & Sahal-Bréchot 1978; Landi Degl’Innocenti 1982; Casini et al. 2003), and in more recent years to the magnetic diagnostics of quiescent prominences and filaments observed at 1083 nm (Trujillo Bueno et al. 2002; Merenda et al. 2006). The system of bound-bound transitions involves the lowest five terms of the triplet species of He I. In order to include photo-ionization and recombination in this model, we added a fictitious bound state,  ${}^3\text{S}_1$ , corresponding to the ground level of He II plus a free electron (with spin parallel to that of the He II ion). The depopulation rate by photo-ionization is given by  $\gamma_{\text{pi}} = \int_{\chi/h}^{\infty} d\nu (4\pi a_{\nu}/h\nu) J(\nu)$ , where  $J(\nu)$  is the intensity of the ionizing radiation averaged over the unit sphere, and  $\chi$  is the ionization potential. The ionization cross-section,  $a_{\nu}$ , for various atomic terms of He I is tabulated by the TOPbase project (e.g., Bauman et al. 2005). In the case of the  $2^3\text{P}$  term, the frequency range over which the cross-section is tabulated goes from the ionization threshold up to  $\sim 3.7$  nm. Unfortunately,

the mean intensity of the solar radiation below the ionization wavelength of 342.2 nm is not well known. UV observations of the solar atmosphere have traditionally focused on limited spectral ranges of particular interest. More complete datasets, covering the whole UV spectrum down to  $\lambda \sim 1$  nm (Eparvier & Woods 2003), are integrated over the solar disk, and do not distinguish the output of the quiet Sun from that of active regions (although they account for variability of the irradiance during the solar cycle). Figure 2 shows the photo-ionization rate,  $\gamma_{\text{pi}}$ , of the He I terms as a function of the effective (Planckian) temperature of the plasma contributing the ionizing radiation. We see that  $\gamma_{\text{pi}} \sim \gamma_u$  at effective temperatures of  $10^5$  K or larger. On the other hand, the effective temperature of the UV emitting solar plasma, as estimated by the integrated number of UV photons detected above the Earth's atmosphere (Eparvier & Woods 2003), is smaller by at least one order of magnitude. Therefore the ionizing UV radiation cannot play a major role in the depolarization of the He I  $\lambda 10830$  levels.

The depolarizing mechanisms considered above seem unable to efficiently destroy atomic polarization generated by resonance scattering, unless one can accept a radical revision of plasma density estimates in AR filaments. The possibility remains that in the AR filament described by Kuckein et al. (2009) atomic polarization was not generated at all. We considered whether the center-to-limb variation (CLV) of the solar atmosphere, which dominates the anisotropy of the illuminating radiation at low heights, may be significantly different in an active region, because of enhanced lateral illumination coming from plages and/or a brighter transition region. However, the few measurements of the CLV in active regions (e.g., Sánchez Cuberes et al. 2002) covering the near-infrared solar spectrum do not seem to support this possibility.

Trujillo Bueno & Asensio Ramos (2007) have proposed that the radiation inside an optically thick filament could be nearly isotropic, and therefore unable to induce atomic polarization. By modeling the filament as a free-standing, plane-parallel slab of optical thickness  $\tau \sim 1$  and constant source function,  $S$ , illuminated by the underlying photosphere with intensity  $I_0$ , they find that the radiation anisotropy inside the slab may be significantly reduced and even become negative (because the illumination is predominantly horizontal). In particular, when  $S \approx I_0$ , the anisotropy inside the filament vanishes. However, if the formation of He I  $\lambda 10830$  is dominated by scattering ( $\gamma_e^{\text{inel.}}/\gamma_u \sim 0.002$  for  $n_e \sim 10^{11} \text{ cm}^{-3}$  typical of prominences), the source function must be modeled accordingly. For example, simply assuming  $S \approx f(\mathbf{d}\Omega/4\pi) p(\cos \Theta) I$ , where  $p(\cos \Theta)$  is the Rayleigh phase function, the anisotropy rises sharply from about 40% of its optically thin limit close to the lower boundary, to well above the optically thin limit at the free upper boundary. Thus, the anisotropy inside the slab does fall below the optically thin limit, but complete isotropy is never attained. Therefore, although a careful radiative transfer treatment of this problem is important, the atomic depolarization of He I may not depend only on that. Moreover, the inversions presented by Kuckein et al. (2009) indicated that the average optical depth of the filament was sizably smaller than 1, further reducing the depolarizing role of radiative transfer.

The preceding analysis motivated us to consider a mechanism of depolarization not commonly included in polarimetric diagnostics, namely, that the depolarization of the He I levels is due

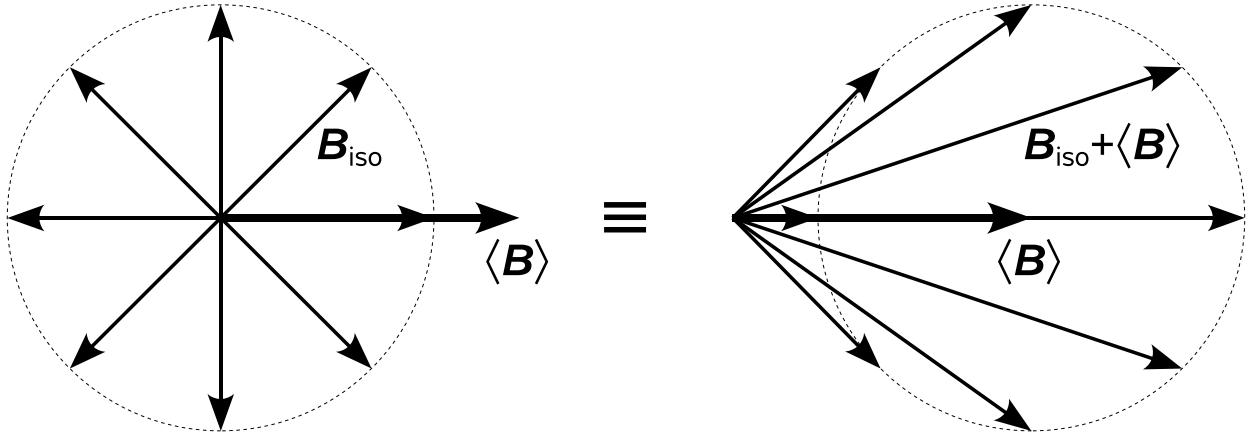


Fig. 3.— Quasi-random magnetic field model (right), obtained by adding a perfectly isotropic (random) field,  $\mathbf{B}_{\text{iso}}$ , to the inferred mean field,  $\langle \mathbf{B} \rangle$  (left).

to the presence of a significant random component in the magnetic field inferred from spectropolarimetric observations. Both observation and theory support the idea that solar magnetic fields, even in the quasi-steady state, are chaotic and dynamic on small spatial and temporal scales. The quiescent-prominence movies made by Hinode/SOT at unprecedented high temporal and spatial resolutions have revealed the extreme complexity and rapid evolution of filamentary prominence plasma (Berger et al. 2008). The long lifetime of a quiescent prominence, days to weeks, implies a large-scale, stable magnetic topology, but which is separate from its significantly entangled and rapidly evolving structures at subsecond scales. MHD waves and oscillations, together with rising and descending plumes, develop ceaselessly in the macroscopic prominence structure. Although the AR filament described by Kuckein et al. (2009) is a class of prominence distinct from the quiescent prominences, we may expect the average field inferred from observation to be co-existing with a small-scale, random component of a comparable field intensity. In the extremely low- $\beta$ , electrically highly conducting environment of the AR atmosphere above the photosphere, current sheets are expected to form densely within any volume pervaded by a magnetic field endowed with a complex topology (Parker 1994; Janse & Low 2009). As these sheets dissipate to heat the atmosphere quiescently, new sheets form without necessarily producing a major flare. The small-scale and rapidly evolving fields associated with a complexity of current sheets are naturally of an intensity comparable to the mean field, and could be the origin of the quasi-random magnetic field we consider here.

Following this picture, we have calculated the emergent Stokes profiles from a homogeneous slab, assuming that the He I atoms are subject to the mean field inferred from the observations plus a completely random (hence, isotropic) field of a given strength. This is also equivalent to assuming a specific non-isotropic distribution of magnetic fields with varying strength, resulting exactly in the observed mean field (Fig. 3). It can be argued that this model is very likely an oversimplification of the real, quasi-random field occurring in prominences. However, its main

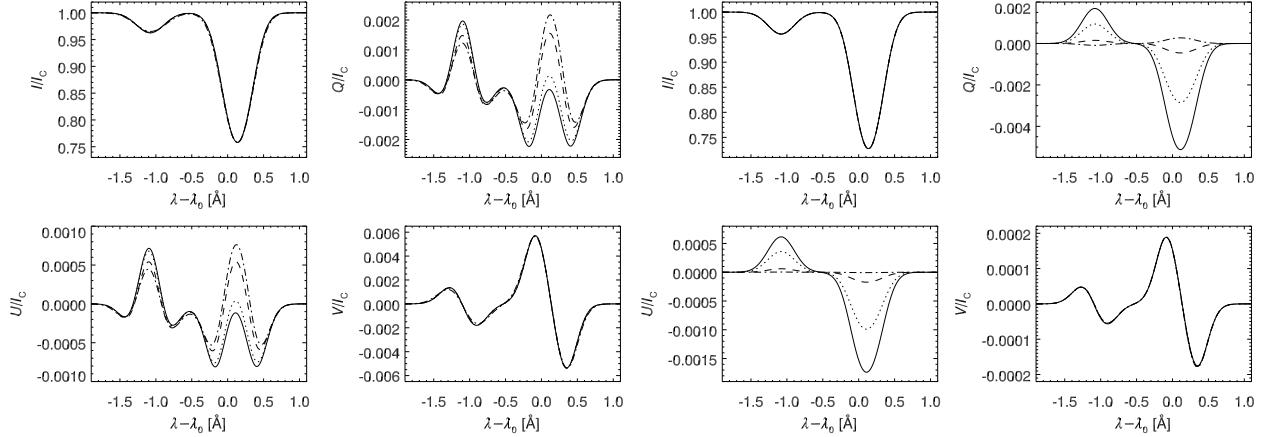


Fig. 4.— Examples of Stokes profiles of He I  $\lambda 10830$  observed on the disk, in the presence of a nearly horizontal magnetic field plus a completely isotropic field of various strengths. *Left:*  $\langle B \rangle = 700 \text{ G}$ ,  $B_{\text{iso}} = 0 \text{ G}$  (continuous curve), 200 G (dotted curve), 500 G (dashed curve), 1000 G (dashed-dotted curve). *Right:*  $\langle B \rangle = 20 \text{ G}$ ,  $B_{\text{iso}} = 0 \text{ G}$  (continuous curve), 10 G (dotted curve), 20 G (dashed curve), 100 G (dashed-dotted curve).

purpose is to illustrate in the simplest way the depolarizing effect of such a field. There is no difficulty in principle in calculating the same effect also for more complicated field distributions. Figure 4 (left) shows the emergent Stokes profiles for such a distribution of magnetic fields, resulting in an almost horizontal mean field of 700 G, similar to those described by Kuckein et al. (2009). The four overplotted profiles illustrate the depolarizing effect induced by the inclusion of an isotropic field of 200, 500, and 1000 G, as well as the case where only the mean field is present. The level of atomic depolarization inferred from the observations corresponds to an isotropic field between 500 and 1000 G, in agreement with the proposed picture of a very entangled, strong field occurring in the filament plasma. Figure 4 (right) also shows the expected effects of atomic depolarization in the presence of a quasi-random field averaging to a nearly horizontal, ordered magnetic field with a strength of 20 G, typical of quiescent prominences and spicules. Especially at such small field strengths, the inference of the magnetic field by the Hanle effect becomes very sensitive to the presence of additional atomic depolarizing processes.

The successful explanation of atomic depolarization by a quasi-random magnetic field stresses the importance to include unresolved fields in the polarimetric diagnostic investigation of the solar atmosphere. The depolarization effect of a completely turbulent magnetic field has been studied in detail (e.g., Stenflo 1994; Landi Degl'Innocenti & Landolfi 2004), and has also found many applications in the study of quiet-Sun magnetism (see, e.g., the review by Trujillo Bueno, Asensio Ramos, & Shchukina 2006). In contrast, to our knowledge, no general account has been given in the past of similar depolarization effects produced by a field that is significantly entangled at scales below the temporal and spatial resolutions of spectro-polarimetric observations, but which averages at a finite, mean field when integrated over those scales. Such mean field, which determines the large-scale evolution

of the plasma, remains within the grasp of the traditional diagnostics based on the Zeeman and Hanle effects. On the other hand, the signature of atomic depolarization—like in the observations described by Kuckein et al. (2009)—finds a very simple and direct interpretation in terms of the strength of a completely random field unresolved to the observations. This scenario provides a very appealing interpretational framework for the highly dynamical events observed at high temporal and spatial resolution with Hinode/SOT, e.g., in quiescent prominences and spicules (Berger et al. 2008), thus opening a new path for the polarimetric study of highly structured plasmas.

Of course, this new insight comes at the cost of introducing an additional degree of freedom in the magnetic diagnostics of chromospheric fields. For this reason, we strongly advocate that future research programs need to take full advantage of multi-line spectro-polarimetry, e.g., through simultaneous observations of He I  $\lambda 10830$  and D<sub>3</sub> in prominences and spicules, or He I  $\lambda 10830$  and H $\alpha$   $\lambda 6563$  in filaments and the chromosphere. In fact, such capability is already been pursued at the French-Italian solar telescope THÉMIS, and will be the normal mode of operation of HAO's Promincence Magnetometer (ProMag; Elmore et al. 2008), soon to be deployed. We expect that this type of multi-line diagnostics of chromospheric fields will fully come to fruition with the large solar facilities of the next generation, like ATST, EST, and COSMO.

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